A CHS based PID Controller for Unified Power Flow Controller

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***Abstract*-This paper presents a method for designing of proportional-integral-derivative (PID) controller based on unified power flow controller (UPFC) using chaotic harmony search algorithm (CHS) for damping of low frequency oscillations (LFO) in a power system. The main aim of this paper, optimization of selected gains with the time domain-based objective function which is solved by chaotic harmony search algorithm. The performance of the proposed single-machine infinite-bus system (SMIB) equipped with UPFC controller- based PID controller is evaluated under various disturbances and operating conditions. The effectiveness of the proposed UPFC controller based on PID controller to damp out of oscillations over a wide range of operating conditions and variation of system parameters is showed in simulation results and eigenvalue analysis.**

***Index terms*- UPFC, Chaotic harmony search, PID controller, SMIB system, LFO**

I. Introduction

UPFC is a kind of FACTs devices that it can be used for voltage regulation compensation, phase shifting regulation, impedance compensation and reactive compensation [1]. UPFC has some great feature but first capability of it is independent controlling of real and reactive power flows in the transmission system [2]. Now days UPFC's utilize move forward to the secure and economic operation in new power systems. Several controlling methods for FACTs devices have been introduced. An assessment of the effects of power system stabilizer (PSS) and static phase shifter (SPS) control using simulated annealing (SA) in [3] has been carried out. Problem of the STATCOM state feedback design based on zero set concept coming in [4]. Particle swarm optimization (PSO) for achieved output feedback parameters of UPFC in [5] is used.

In this article a single machine infinite bus (SMIB) as a power system is considered. After making a linear system around the operating condition with a disturbance in different loading situation that are converted to optimizing problem. For solving these kinds of problem, several algorithms are recommended in the above but in this paper chaotic harmony search (IHS) technique is used. By considering available parameter Äù as a input of PID controller this procedure is carried out. In this paper two UPFC inputs applied independently that connected to the output c(δ_E, m_B)ntroller. Finally the effectiveness of this work by result evaluation and comparison of performance indices is showed.

II. Chaotic harmony search algorithm

This section describes the proposed chaotic harmony search (CHS) algorithm. First, a brief overview of the IHS is provided, and finally the modification procedures of the proposed CHS algorithm are stated.

A. Improved Harmony Search Algorithm

Fundamental of this method is based on the concept in search of a suitable state in music. In that mean's how a musician with different search modes to reach its desired state. To implement the above concepts in form of algorithm ahead will several steps. This process generally in the form of the following five steps will be implemented [7- 9].

1. Initialize the problem and algorithm parameters.
2. Initialize the harmony memory.
3. Improvise a new harmony.
4. Update the harmony memory.
5. Check the stopping criterion.

A.1. Initialize the problem and algorithm parameters

At this stage initialize all the algorithm parameters are carried out. These parameters can be defined by the following terms [7- 9]:

HMS: Harmony memory size or the number of solution vectors in the harmony memory
HMCR: Harmony memory considering rate
PAR : Pitch adjusting rate
NI : Number of improvisations
N : Number of decision variables

A.2. Initialize the Harmony Memory

The harmony memory (HM) is a matrix include of independent variables which in this stage are selected randomly. Each row of this matrix indicates a solution to the problem.

$$HM = \begin{pmatrix} x_1^1 & \cdots & x_N^1 \\ \vdots & \ddots & \vdots \\ x_1^{HMS} & \cdots & x_N^{HMS} \end{pmatrix} \qquad (1)$$

A.3. Improvise a New Harmony

Producing a new harmony is called improvisation. The new harmony vector $x' = (x_1', x_2', \ldots, x_N')$ is achieved by three parameters: harmony memory consideration rate, pitch adjustment rate and random selection. In the improved harmony search algorithm two parameters in each iteration are changed. These parameters are pitch adjustment rate (PAR) and bandwidth (bw). The form of the changing these parameters is shown at below equations:

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$$PAR = PAR_{min} + \frac{(PAR_{max} - PAR_{min})}{NI} \times gn \qquad (2)$$

Where:

PAR pitch adjusting rate for each generation
PAR_{min} minimum pitch adjusting rate
PAR_{max} maximum pitch adjusting rate
NI number of solution vector generations
gn generation number

$$bw(gn) = bw_{max} \cdot e^{\left(gn. \frac{\ln\left(\frac{bw_{min}}{bw_{max}}\right)}{NI}\right)} \qquad (3)$$

Here
bw(gn) bandwidth for each generation
bw_{min} minimum bandwidth
bw_{max} maximum bandwidth

A.4. Update the Harmony Memory

In the updating harmony memory stage, with placing new value ($x' = (x_1', x_2', \ldots, x_N')$) on the objective function if objective function value is better than the previous case it must be old harmony out of memory and its new value will replaced.

A.5. Check Stopping Criterion

If the stopping criterion (maximum number of improvisations) is satisfied, computation is terminated. Otherwise, steps 3 and 4 are repeated.

B. Proposed Method

In numerical analysis, sampling, decision making and especially heuristic optimization needs random sequences with some features. These features consist a long period and good uniformity. The nature of chaos is apparently random and unpredictable. Mathematically, chaos is randomness of a simple deterministic dynamical system and chaotic system may be considered as sources of randomness [7]. There are many methods for generating of random numbers but here used sinusoidal iterator for chaotic map [7]. It is represented by:

$$X_{n+1} = a x_n^2 \sin(\pi x_n) \qquad (4)$$

When a = 2.3 and x_0=0.7 it has the simplified form represented by:

$$X_{n+1} = \sin(\pi x_n) \qquad (5)$$

It generates chaotic sequence in (0, 1). Initial HM is generated by iterating the selected chaotic maps until reaching to the HMS as shown in flowchart Fig.1 [7]:

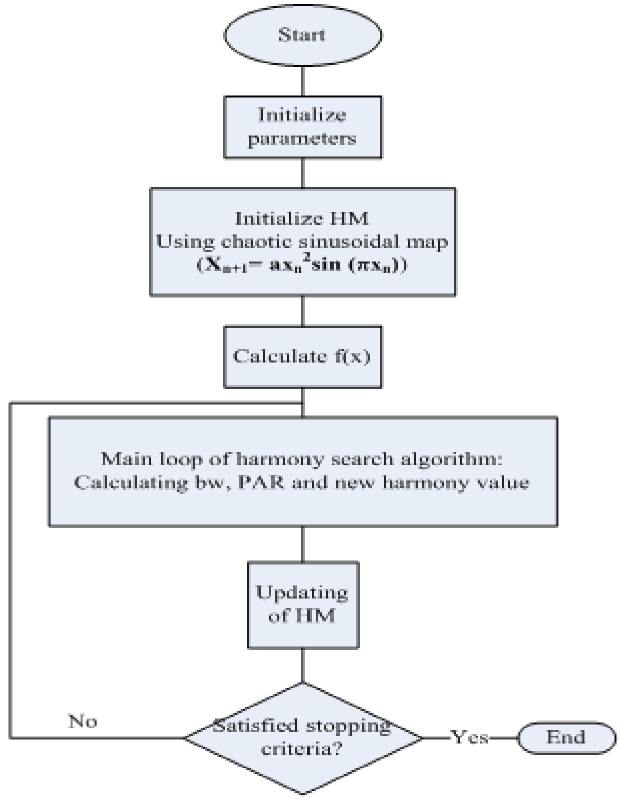

Figure 1. Flowchart of the chaotic harmony search

III. Modeling the Power System Under Study

The system in this article is a single machine infinite bus (SMIB) with UPFC installed as shown in Fig. 2 [5]. For analysis and enhancing small signal stability of power system through UPFC, dynamic relation of system is needed. To have these relations through park transformation and ignoring resistance of both boosting and exciting transformers can be achieve following equations [5, 6]:

$$\begin{pmatrix} v_{Etd} \\ v_{Etq} \end{pmatrix} = \begin{pmatrix} 0 & -x_E \\ x_E & 0 \end{pmatrix} \begin{pmatrix} i_{Ed} \\ i_{Eq} \end{pmatrix} + \begin{pmatrix} \frac{m_E \cos(\delta_E) v_{dc}}{2} \\ \frac{m_E \sin(\delta_E) v_{dc}}{2} \end{pmatrix} \qquad (6)$$

$$\begin{pmatrix} v_{Btd} \\ v_{Btq} \end{pmatrix} = \begin{pmatrix} 0 & -x_B \\ x_B & 0 \end{pmatrix} \begin{pmatrix} i_{Bd} \\ i_{Bq} \end{pmatrix} + \begin{pmatrix} \frac{m_B \cos(\delta_B) v_{dc}}{2} \\ \frac{m_B \sin(\delta_B) v_{dc}}{2} \end{pmatrix} \qquad (7)$$

$$\dot{v}_{dc} = \frac{3m_E}{4C_{dc}} \begin{pmatrix} \cos\delta_E & \sin\delta_E \end{pmatrix} \begin{pmatrix} i_{Ed} \\ i_{Eq} \end{pmatrix} + \frac{3m_B}{4C_{dc}} \begin{pmatrix} \cos\delta_B & \sin\delta_B \end{pmatrix} \begin{pmatrix} i_{Bd} \\ i_{Bq} \end{pmatrix} \qquad (8)$$

where v_{Et}, i_E, v_{Bt}, and i_B are the excitation voltage, excitation current, boosting voltage, and boosting current, respectively; C_{dc} and v_{dc} are the dc link capacitance and voltage [5]. The non linear model of the SMIB system introduced Fig.2 as shown following equations:

$$\dot{\omega} = \omega_b(\omega - 1) \qquad (9)$$

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$$\dot{\omega} = \left(\frac{P_m - P_e - D\Delta\omega}{M}\right) \quad (10)$$

$$\dot{E}'_q = \left(\frac{E_{fd} + (x_d - x'_d)i_d - E'_q}{T'_{do}}\right) \quad (11)$$

$$\dot{E}_{fd} = \left(\frac{-E_{fd} + K_a(v_{ref} - v_t + U_{pss})}{T_a}\right) \quad (12)$$

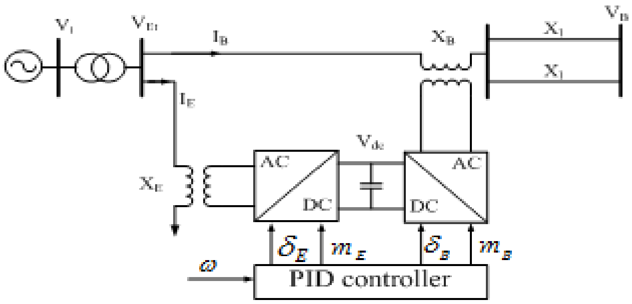

Figure 2. SMIB power system equipped with UPFC

A. *Power System Linearized Model*

With applying linearization process around operating point on under study system, state space model of system according below relation can be achieved.

$$\dot{X} = AX + BU \quad (13)$$

Where, the state vector x, input vector u, A and B are:

$$x = (\Delta\delta \;\; \Delta\omega \;\; \Delta E'_q \;\; \Delta E_{fd} \;\; \Delta v_{dc}) \quad (14)$$

$$u = (\Delta m_E \;\; \Delta\delta_E \;\; \Delta m_B \;\; \Delta\delta_B) \quad (15)$$

$$A = \begin{bmatrix} 0 & \omega_0 & 0 & 0 & 0 \\ \frac{-K_1}{M} & 0 & \frac{-K_2}{M} & 0 & \frac{-K_{pd}}{M} \\ \frac{-K_4}{T'_{do}} & 0 & \frac{-K_3}{T'_{do}} & \frac{1}{T'_{do}} & \frac{-K_{qd}}{T'_{do}} \\ \frac{-K_A K_5}{T_A} & 0 & \frac{-K_A K_6}{T_A} & \frac{1}{T_A} & \frac{-K_A K_{vd}}{T_A} \\ K_7 & 0 & K_8 & 0 & -K_9 \end{bmatrix} \quad (16)$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ \frac{-K_{pe}}{M} & \frac{-K_{p\delta e}}{M} & \frac{-K_{pb}}{M} & \frac{-K_{p\delta b}}{M} \\ \frac{-K_{qe}}{T'_{do}} & \frac{-K_{q\delta e}}{T'_{do}} & \frac{-K_{qb}}{T'_{do}} & \frac{-K_{q\delta b}}{T'_{do}} \\ \frac{-K_A K_{ve}}{T_A} & \frac{-K_A K_{v\delta e}}{T_A} & \frac{-K_A K_{vb}}{T_A} & \frac{-K_A K_{v\delta b}}{T_A} \\ K_{ce} & K_{c\delta e} & K_{cb} & K_{c\delta b} \end{bmatrix} \quad (17)$$

IV. PID Controller for UPFC

The eigenvalues of the state matrix A that are called the system modes define the stability of the system. By using PID controller, can move the unstable mode to the left-hand side of the complex plane in the area of the negative real parts. A PID controller has the following structure:

$$G_{PID} = K_p + \frac{K_i}{s} + K_d s \quad (18)$$

By properly choosing the PID gains (K_p, K_i, K_d), the eigenvalues of system are moved to the left-hand side of the complex plane and the desired performance of controller can be achieved. UPFC controllers (m_B, m_E, δ_B and δ_E) are four parameters that can help them, reach the above goals mentioned but in this paper the two UPFC's controller inputs (δ_E, m_B) separately under various operating conditions is considered. In this study for solving optimization problem and reach the global optimal value of coefficients K, CHS algorithm is used.

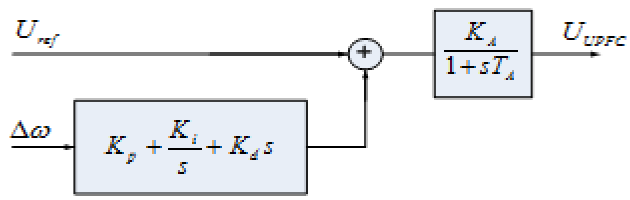

Figure 3. UPFC with PID controller

in form Integral of Time Multiplied Absolute value of the Error (ITAE) as the objective function for the algorithm is selected. The objective function is defined as follows:

$$\text{Objective function} = \int_0^{tsim} t|\Delta\omega|dt \quad (19)$$

In the above equations, t_{sim} is the time range of simulation. The design problem can be formulated as the following constrained optimization problem, where the constraints are the controller parameters bounds:

$$K_p^{min} \le K_p \le K_p^{max} \quad (21)$$

$$K_i^{min} \le K_i \le K_i^{max} \quad (22)$$

$$K_d^{min} \le K_d \le K_d^{max} \quad (23)$$

Typical ranges of the optimized parameters are [0.01–150] for K_p and [-5 – 5] for K_i and [-10 – 10] for K_d. The optimization of UPFC controller parameters is carried out by evaluating the objective cost function as given in Eq. (19). The operating conditions are considered as, Normal, light and heavy load respectively:

P = 0.80 pu , Q = 0.114 pu and x_L = 0.5 pu.
P = 0.2 pu, Q = 0.007 pu and x_L = 0.5 pu.
P = 1.20 pu, Q = 0.264 pu and x_L = 0.5 pu.

In order to acquire better performance, the parameters of CHS algorithm are showed in table I.

Table I.
Value of CHS Algorithm Constant Parameters

parameters	HMS	HMCR	PAR_{min}	PAR_{max}	bw_{min}	bw_{min}
value	20	0.9	0.25	0.55	1e-4	5

In optimizing values of the controller parameters, algorithm must be repeated several times. Finally values for PID control gains are selected. Optimal values in normal load are shown in the table II:

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TABLE II.
THE OPTIMAL GAIN ADJUSTING OF THE PROPOSED CONTROLLERS

controller	K_p	K_i	K_d
δ_E	95.244	0.845	1.024
m_B	145.81	1.027	-9.680

V. TIME DOMAIN SIMULATION

System performance with the values obtained for the optimal PID by applying a disturbance at t = 1 for 6 cycles is evaluated. The speed and generator power deviation at normal, light and heavy load with the proposed controller based on the δ_E and m_B are shown in Fig. 4 and Fig.5 respectively. To demonstrate performance robustness of the proposed method, two performance indices: the ITAE and Figure of Demerit (FD) based on the system performance characteristics are defined as [8]:

$$ITAE = 10{,}000 \int_0^{10} t(|\Delta\omega| + 0.03|\Delta P_e|)dt \quad (24)$$

$$FD = (1000 \times OS)^2 + (3000 \times US)^2 + T_s^2 \quad (25)$$

Where ($\Delta\omega$) is the speed deviation, (ΔP_e) is the generator power deviation, Overshoot (OS), Undershoot (US) and T_s is the settling time of speed deviation for the machine is considered for evaluation of the ITAE and FD indices. It is worth mentioning that the lower the value of these indices is, the better the system response in terms of time-domain characteristics. It can be seen that the values of these system performance characteristics with the PID δ_E based controller are much smaller compared to PID m_B based controller.

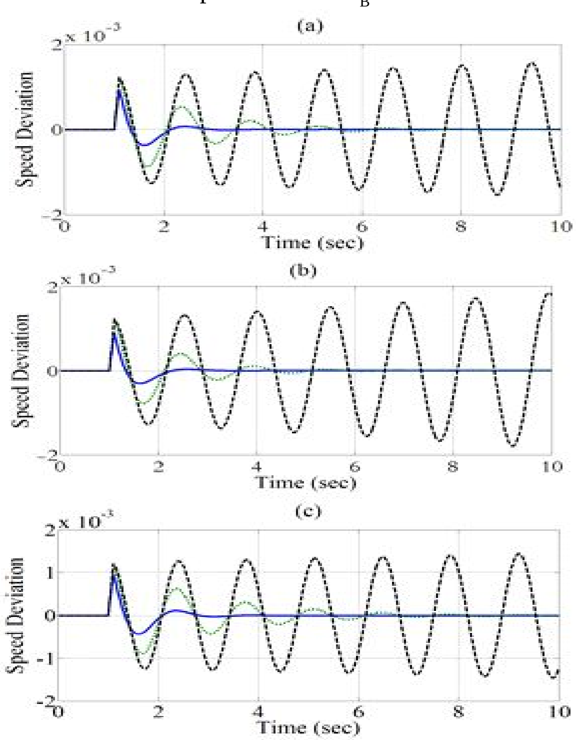

Figure 4. Dynamic responses for speed deviation with normal (a), heavy (b) and light load (c): solid (δ_E based controller), dotted (m_B based controller), dashed (without controller)

TABLE III.
EIGENVALUES OF SYSTEM IN DIFFERENT OPERATING CONDITIONS FOR δ_E BASED CONTROLLER

Normal P = 0.8 (pu)	Light P = 0.2 (pu)	Heavy P = 1.2 (pu)
-19.2472	-19.212	-19.2737
-2.205 ± 3.89j	-1.886 ± 4.252j	-2.568 ± 3.226j
-1.2629	-1.277	-1.3248
-0.064	-0.0429	-0.0584

TABLE IV.
EIGENVALUES OF SYSTEM IN DIFFERENT OPERATING CONDITIONS FOR m_E BASED CONTROLLER

Normal P = 0.8 (pu)	Light P = 0.2 (pu)	Heavy P = 1.2 (pu)
-19.323	-19.233	-19.377
-0.629 ± 4.372j	-0.459 ± 4.580j	-0.748 ± 4.008j
-1.0968	-1.2364	-1.0539
-0.0746	-0.0447	-0.0726

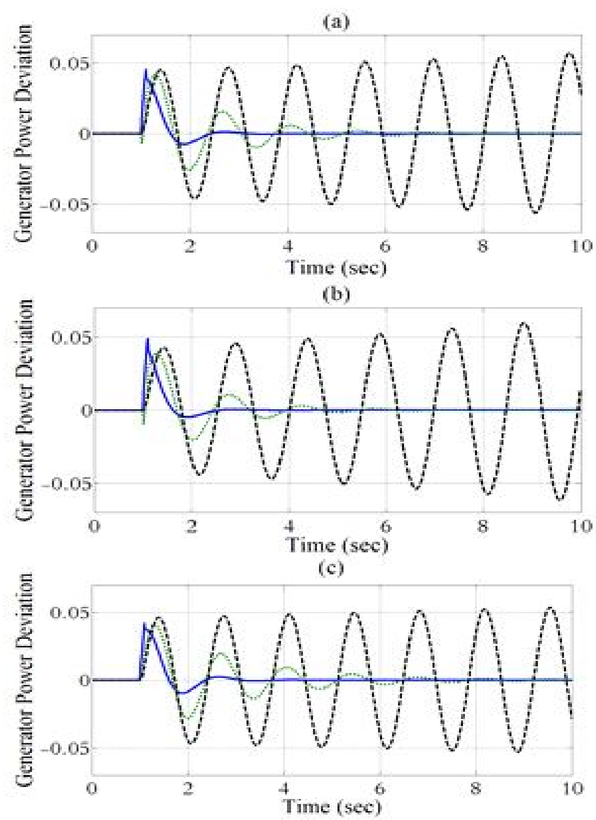

Figure 5. Dynamic responses for generator power deviation with normal (a), heavy (b) and light load (c): solid (δ_E based controller), dotted (m_B based controller), dashed (without controller)

TABLE V.
VALUES OF PERFORMANCE INDICES ITAE AND FD

Controller	normal		light		heavy	
	FD	ITAE	FD	ITAE	FD	ITAE
δ_E	7.85	8.869	9.895	10.07	6.460	7.825
m_B	41.4	26.06	69.45	31.91	29.21	21.07

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Conclusions

The chaotic harmony search algorithm was successfully used for the modeling of UPFC based PID damping controller. For each of the control signals from available state variable $\Delta\omega$ is used. The efficient of the proposed UPFC controller for improving dynamic stability performance of a power system are illustrated by applying disturbances under different operating points. Results from time domain simulation shows that the oscillations of synchronous machines can be easily damped for power systems by this method. To analyze performance of UPFC's controller two indicators were used. These indices in terms of 'ITAE' and 'FD' are introduced that this indices demonstrate that PID with δ_E based damping controller is superior to m_B based damping controller.

Appendix A

Table.vi. System Parameters

Generator	$M = 8$ MJ/MVA, $T'_{do} = 5.044$ s $X_d = 1$pu, $X_q = 0.6$pu, $X'_d = 0.3$pu
Excitation system	$K_A = 10$, $T_A = 0.05$ s
Transformers	$X_t = X_E = X_B = 0.1$pu
Transmission line	$X_L = 0.5$ pu
Operating condition	$P = 0.8$ pu, $V_b = 1$ pu
DC link parameter	$V_{DC} = 1$ pu, $C_{DC} = 1$ pu
UPFC parameter	$\delta_E = -85.35$, $\delta_B = -78.21$, $T_s = 0.05$ $m_E = 0.4$, $m_B = 0.08$, $K_s = 1$

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